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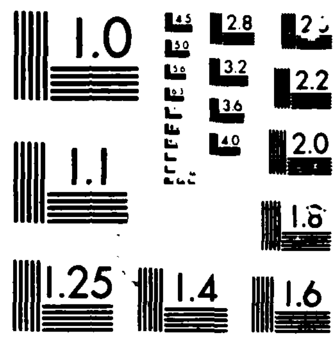
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NAVY EXPERIMENTAL DIVING UNIT
REPORT NO. 9-86

MK 16 MOD 0 UNDERWATER BREATHING APPARATUS: MANNED AND UNMANNED CANISTER DURATION

By

LCDR M. E. KNAFELC, MC, USN

NAVY EXPERIMENTAL DIVING UNIT

DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
PANAMA CITY, FLORIDA 32407-5001

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26 September 1986

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The CO_2 absorbent canister duration of the MK 16 closed-circuit Underwater Breathing Apparatus (UBA) was evaluated using manned and unmanned testing procedures. The results demonstrated that the MK 16 is capable of supporting the diver to the limit line of the HVAL21 constant .7 ppO_2 HeO_2 Decompression Table in temperatures 4.4°C (40°F) and above. The only exception is the 40 FSW for 370 min profile, which is restricted to 300 min.

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ABSTRACT

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KEY WORDS:

MK 16
closed-circuit UBA
canister duration
CO_2 absorbent
oxygen consumption
NEDU Test Plan 86/10

A-1

INTRODUCTION

The MK 16 Mod 0 (MK 16) is a closed circuit underwater breathing apparatus (UBA) which automatically maintains a constant inspired partial pressure of oxygen of 0.75 ± .15 ATA. The apparatus automatically adds oxygen to the breathing loop to replace the oxygen consumed by the diver and adds diluent gas to maintain volume. A CO_2 absorbent canister removes the diver's metabolically produced CO_2. The design depth capability is 150 FSW using nitrogen-oxygen as the breathing medium and 300 FSW using helium-oxygen.

Results of previous studies on the pre-production and first article models of the MK 16 indicate that the underwater duration of the MK 16 Mod 0 was limited by the carbon dioxide absorbant canister rather than the quantity of gas in the oxygen or diluent bottles (1). The purpose of this study was to conduct unmanned and manned evaluations of the certified MK 16 canister duration. The results of this study are intended to provide the U.S.Navy EOD community with realistic performance expectations of the MK 16 for purposes of operational planning.

PROCEDURES

UNMANNED STUDIES

The first phase of this evaluation was unmanned canister duration studies. A breathing machine (Reimers Consultants, Falls Church, VA) simulated diver inhalation and exhalation. The CO_2 produced by a working diver was simulated by injecting CO_2 with a relative humidity of 90 ± 2% at a rate of 2.0 standard liters per minute (slpm) for 6 minutes alternating with 0.9 slpm for 4 minutes, for an overall injection rate at 1.57 slpm. This schedule simulates the standard manned canister durations done previously by the Navy Experimental Diving Unit (NEDU). The detailed unmanned testing procedures are published in NEDU Report 3-81. For these tests an EX 15 Mod 1 (EX 15) with a CO_2 absorbant canister and breathing loop identical to the MK 16 was used due to the unavailability of the MK 16 at the time of testing. The backpack cover was not used because of its improper fit after the modification. The unmanned evaluation of the EX 15 canister's duration was done at a selected range of depths between 30 and 300 FSW and temperatures between 29 and 70°F (NEDU Test Plans 84-06 and 85-35). The gas mixture was HeO_2 (84/16 mix).

A second study simulating a modified dive profile was also performed. The EX 15 was compressed to 300 FSW for either 20 min., 40 min., or until canister breakthrough (0.5% SEV CO_2). Then the UBA was decompressed to 100 FSW and remained there until the canister effluent reached 1.0% SEV CO_2. Breakthrough was arbitrarily defined as 0.5% SEV CO_2 based on previous canister studies which showed a rapid rise in CO_2 after that point. Compression and decompression rates were 60 feet per minute. Test temperatures were 35 and 40°F.

MANNED STUDIES

The second phase of testing was manned studies. All diver-subjects were military trained divers and familiar with operating the MK 16. The dives were conducted during the decompression phase of a 31 day helium-oxygen saturation dive within the Ocean Simulation Facility (OSF) wet chamber at simulated depths of 300 and 100 FSW (NEDU Test Plan 86/10). The water temperature was 40°F (4.4 ± 1°C).

Two bicycle ergometers adjusted to a 37° heads-up position were placed within the wet chamber. This allowed two divers to excercise simultaneously at a 50 watt, 55-65 rpm, work rate on a 6 min. work, 4 min. rest schedule. From past experience this schedule produced an average O_2 consumption of 1.5 slpm (2). This schedule was continued until the canister effluent reached 1.5% SEV CO_2. The divers were rotated approximately every 2 hrs. to minimize diver fatigue. The maximum time spent changing out the divers was 1 min. to ensure that no significant regeneration of the canister would occur. When necessary during the dive, the diluent or oxygen bottles were changed. Bottle pressures, battery voltages, and time were recorded when divers or equipment were changed. Data recording was not interrupted during changes. A standby diver with communications to the surface was ready to assist the MK 16 divers during testing.

The divers used a NRV hot-water suit to ensure they would not have to abort the study due to cold. Since canister duration may be affected by temperature, thermal readings near the canister were taken during the training phase. Temperature readings using a YSI 702A thermistor probe (Yellow Springs Instrumentation, Yellow Springs, OH) placed on the side or top of the canister were made. The diver wore either the hot-water suit, which circulated hot water around him and shunted hot water directly into the wet chamber, or an Imperial dry suit. The greatest variance in temperature reading between the two suits of .6°C was deemed insignificant.

Each UBA was set up at 1.0 ATA according to the MK 16 MOD 0 UBA OPERATIONS AND MAINTENANCE MANUAL (SS 600-AH-MMA-010, 1 May 1985). A freshly charged primary battery (Power-Sonic Model PS-610) and four new secondary batteries (1.5v carbon zinc) were used for each dive. The canisters were packed with HP Sodasorb (Dewey and Almy Chemical Division, W. R. Grace and Co., Atlanta, GA) of the same expiration date and their weight recorded on the morning of each dive. The diluent gases used were 92.6/7.4% helium-oxygen at 300 FSW and 81.4/18.6% helium-oxygen at 100 FSW. These mixtures were chosen to provide diluent gas with an oxygen partial pressure of 0.75 ATA at each test depth so that any oxygen lost from the UBA due to mask clearing, etc. would be made up from the diluent bottle and not the oxygen bottle distorting oxygen consumption calculations.

The oxygen bottle pressure was measured with a Validyne DP15 Pressure Transducer equipped with a 3000 psig ± 1% diaphragm mounted to the MK 16. Calibration from 0-2500 psi was done using a Mensor 11600 digital pressure gauge (2500 psi ± 0.04%). The linear regression of the Validyne voltage vs.

the digital pressure gauge reading was calculated by an HP-1000 computer (Hewlett Packard, Cupertino, CA). A plot of oxygen bottle pressure vs. time was made from which oxygen consumption was estimated is described in reference 3.

Two gas sample lines, canister influent and canister effluent, were attached to the MK 16 breathing hoses. A Perkin Elmer MGA 1100 mass spectrometer was used to analyze for O_2, CO_2, and N_2 for each diver. The sample flow rate was 0.5 SLPM ATP. A reading was taken every 30 seconds and recorded on the HP-1000 computer. The mass spectrometers were calibrated prior to each canister study and checked every 30 min. during the study.

Testing of the canister duration was continued until the canister's effluent CO_2 reached 1.5% SEV continuously for at least one minute or upon request by the diver.

RESULTS

UNMANNED STUDIES

The time to canister breakthrough (0.5% SEV CO_2) at various depths and temperatures are given in Table 1. At 100 FSW and shallower the canister is relatively temperature insensitive over the temperature range of 29-70°F. Figure 1 shows that below 100 FSW, temperature affects duration significantly. At a given temperature, as depth increases, canister durations decrease.

Several tests were done at various depths which showed deviations from the averages given in Table 1. Canister durations which varied more than 20 min. from a set of studies under similar conditions were discarded. Such discrepancies were due to computer failure which necessitated manual control probably resulting in variances in the CO_2 injection rates between the tests.

The canister duration using the modified dive profiles are given in Table 2. There appears to be some canister regeneration upon decompression from 300 FSW to 100 FSW. However, in 35°F water temperature the time spent at 300 FSW did not affect the final canister duration, though the overall canister duration is much shorter than the 100 FSW studies. At 40°F the 300 FSW excursion did not affect the canister duration; the performance was similar to that seen at 100 FSW.

TABLE 1

UNMANNED MK 16 CANISTER DURATIONS AT VARIOUS DEPTHS AND TEMPERATURES
Time (min.) to Canister Effluent of .5% SEV CO_2

Depth (FSW)	Temperature (°F) 29	35	40	50	60	70
30			279			
100	273	285				293
150	186	243	276			
200	139			210	299	
300	71	141	114	120		342

NOTE: Each value represents the average time of two dives that had canister durations within 20 min. of each other.

TABLE 2

UNMANNED MK 16 CANISTER DURATIONS USING MODIFIED DIVE PROFILES

Time spent at 300 FSW before decompression to 100 FSW	Time (min.) to .5% SEV CO_2
35°F	
Breakthrough (117 min.)	185
20 min.	175
40 min.	174
40°F	
20 min.	272

NOTE: Each value represents the average time of two dives that had canister durations within 20 min. of each other.

MANNED STUDIES

The canister durations and calculated oxygen consumptions for the 3 dives completed at 300 FSW and the 5 dives at 100 FSW are given in Table 3. The mean time to canister breakthrough at 300 FSW was 280 ± 40 min at 100 FSW. The actual curve of canister effluent CO_2 versus time are shown in Figures 2 through 9. From these curves it can be seen that it took approximately 1 to 1.5 hrs after breakthrough for the canister effluent to reach 1.5% SEV CO_2.

The overall oxygen consumption rate for a 50 watt work/rest cycle was estimated from the following formula which assumes no gas leaks from the UBA other than the known gas sample rates:

$$\dot{V}_{O_2} = (\Delta P/T) \cdot Vb \cdot [273/(T \pm 273)] - Vs \cdot F_{O_{2_s}}$$

where:

$\dot{V}_{O_2}$ = O_2 consumption (slpm)
$\Delta P/T$ = slope of O_2 pressure plot (ATA/min)
Vb = O_2 bottle floodable volume (2.868ℓ)
T = O_2 bottle temperature (assumed equal to the wet pot temp. °C)
Vs = UBA gas sample rate (1 slpm)
$F_{O_{2_s}}$ = oxygen fraction in the gas sample

Overall average calculated oxygen consumption rates for the entire manned study is given in Table 3.

TABLE 3

RESULTS OF MANNED MK 16 CANISTER DURATION STUDIES

NOTE: Times listed were determined when the canister's effluent reached the desired endpoint and sustained it for 2 min.

300 FSW/40°F

Run	Time (min) Canister Effluent 0.5% SEV	Canister Effluent 1.5% SEV	Oxygen Consumption (ℓ/min)	Figure
1	323	386	1.23	2
2	243	301	1.52	3
3	275	328	1.50	4
	280 ± 40	338 ± 43	1.42 ± .16	

100 FSW/40°F

Run	Time (min) Canister Effluent 0.5% SEV	Canister Effluent 1.5% SEV	Oxygen Consumption (ℓ/min)	Figure
1	286	340	1.53	5
2	360	450	1.40	6
3	265	349	1.42	7
4	244	327	1.41	8
5	317	*	1.74	9
	294 ± 46	366 ± 56	1.5 ± .14	

* Diver aborted dive due to increased breathing resistance.

DISCUSSION

After reviewing the unmanned data several observations can be made:

1. Canister durations for dives 100 FSW and shallower are unaffected by temperature, if the diver has adequate thermal protection.

2. Dives can be planned as deep as 150 FSW without temperature considerations if the water temperature is at least 40°F. This is significant because 150 FSW is the deepest decompression stop in the HVAL21 0.7 ppO_2 HeO_2 Decompression Tables (HVAL21). The time that can be spent at 150 FSW in 40°F is approximately the same time that can be spent at 100 FSW and shallower in any temperature.

3. In 40°F water temperature a 20 minute bottom time at 300 FSW does not affect the canister's duration. The canister duration is approximately that seen at 100 FSW.

These characteristics can greatly simplify the operational planning for the MK 16. If the water temperature is 40°F or greater one can expect the canister to last approximately the same time regardless of the maximum depth of the dive.

Reviewing the previous data, we can conclude that the MK 16 canister can support all dive profiles allowed by HVAL21, the only exception is the 40 FSW for 370 min. profile. Although the average canister duration is less than 5 hrs to breakthrough, analysis of the individual CO_2 curves show that no diver would inspire a dangerous level of CO_2 during a 5 hr exposure. Moreover, the CO_2 load placed on the canister during this study is likely to be greater than that would be experienced operationally since the majority of exposure on the longest dives are in decompression where the diver is not ordinarily at work. Dives to 40 FSW or less should be limited to 5 hrs.

At 300 FSW the manned canister duration was twice that predicted by the unmanned studies. The greatest differences in test conditions between manned and unmanned studies that may account for this is the assumed respiratory quotient of 1.0 used for unmanned testing. A respiratory quotient of 0.80 is reported by other researchers in the field, (4). The warming effect on the Sodasorb bed by the diver's breath or at least the minimization of canister bed cooling may also account for the increase in canister efficiency experienced during manned testing. Other differences between manned and unmanned testing were: (1) Unmanned studies were done using the EX 15 Mod 1, a modified MK 15 with a MK 16 breathing loop; manned studies used a certified MK 16 (2) In the unmanned studies the EX 15 Mod 1's backpack cover was off because the canister protruded through the cover; in the manned studies the backpack cover was in place. Since the EX 15 and the MK 16 utilized identical breathing loops this should not significantly affect the tests. The temperature around the canister with the backpack cover on was approximately 1°C warmer than the water temperature and therefore has an insignificant affect on canister performance.

During the manned studies it was observed at 300 FSW only a small portion of the sodasorb was caked due to excess moisture and probably not utilized completely in the chemical reaction of CO_2 absorption, as indicated by a lack of color indicator change. At 100 FSW a large portion of the canister was caked and had no color change. The source of the moisture is not only the diver's respiratory water loss but saliva which was noted to have drained down the exhalation hose as evidenced by the froth in the canister holder during post-dive inspection of the MK 16. The wet area was the lowest part of the canister when worn by a diver in a 37° head-up attitude. An explanation for the difference between the appearance of the sodasorb at different depths may be that the 300 FSW dives used new MK 16 absorbent pads, while the 100 FSW dives reused the pads after drying them in the air overnight. Reusing the MK 16 pads is current fleet practice. Close inspection of the reused pads revealed that sections had broken away after use. Thus the current MK 16 pads appear to deteriorate rapidly with exposure to the caustic sodasorb. Therefore, new or better absorbent pads which ..eep the sodasorb bed more dry and resist deterioration should be used to permit the maximum use of the sodasorb and thus maximize canister duration.

In an attempt to identify a better absorbent pad new MK 15 absorbent pads were used for 2 dives. These pads are made of a different material and their form covers the exhalation holes of the MK 16 canister. Unmanned studies indicated they were effective in the MK 15 and do not add to the breathing resistance in that rig, (5). The results were inconsistent. On run 5 at 100 FSW the sodasorb was less wet than in previous dives and breakthrough was 317 min. Run 4 at 100 FSW broke through in 244 min. and the sodasorb appeared as wet as the previous runs using the MK 16 pads. The diver complained of increased breathing resistance upon exhalation. This was accompanied by a sharp rise in the effluent CO2 to 1.5% SEV at which time the dive was halted, figure 8. The other diver experienced difficulty in exhalation after approximately 5 hrs. on the rig resulting in aborting Run 5 right after canister breakthrough. Again a rapid rise of the canister's effluent CO_2 occurred (Figure 9). A possible explanation for the exhalation difficulty and rapid rise in canister effluent CO_2 is that the pads became saturated with water producing a significant back pressure on the exhalation side resulting in inverting the silicon material one-way inhalation hose valve. Thus, an incompetent inspiratory valve can result in partial rebreathing of CO_2 rich gas exhaled into the inspiration hose. The previous unmanned studies injected humidified gas through the breathing loop but it is likely that saliva being added by the diver during manned studies creates a new problem of breathing resistance when the pads become saturated with a combination of water and saliva.

When planning dives of long durations adequate thermal protection must be addressed. The NRV hot-water suit was the only available means to protect the divers during this dive series. Actual fleet operations prohibit this type of surface support. The PDTPS was developed to thermally protect the diver, but its adequacy to reliably support the MK 16 is undetermined.

Overall, the MK 16 functioned satisfactorily. The divers reported that the mouthpiece was uncomfortable and the rig had an increased breathing resistance when the MK 15 absorbent pads were used. During all the MK 16 dives notations were made to evaluate oxygen bottle durations. When a fully charged oxygen bottle (3000 psi) was used on the dive, with an average $^{V}O_2$ 1.5 ℓ/min, the bottle duration was approximately 5 hrs. However, oxygen is utilized during the pre-dive calibration of the MK 16. Therefore, if the same oxygen bottle was used for setting up the MK 16 as used for the dive, with an average $^{V}O_2$ 1.5 ℓ/min, the bottle lasted approximately 4 hrs.

CONCLUSIONS

1. Based on a working scenario using HeO_2 as the breathing gas the MK 16 canister duration is 5 hrs. in temperatures 40°F and above. Depth is not a significant factor within that temperature range. This limit restricts only the 40 FSW for 370 min. profile to 300 min. All other profiles can be dove to the limit line of the HVAL21 Decompression Tables.

2. For temperatures below 40°F, the depth of the dive must be considered. If the dive is 100 FSW or shallower the MK 16 canister will last 5 hrs. for a working diver. Based upon unmanned studies, for excursions below 100 FSW with temperatures between 35 and 39°F, the canister will last 4 hrs. In temperatures between 29 and 34°F, the canister will last only 2 hrs.

3. Because the absorbent pads deteriorate rapidly, resulting in diminished performance or increased breathing resistance, it is recommended that they be used for only one dive. New absorbent materials should be investigated. Pads should be disposable to insure consistent effectiveness and ease maintaince. They should be capable of absorbing water without adding significant resistance to gas flow. New pads should be of the same form and fit as the current MK 16 pads.

4. The amount of backpressure needed to overcome the one-way mushroom valves in the MK 16 should be investigated. The current MK 16 mushroom valve is made of a very flexible silicon material measuring 1.38 inch diameter. There is little overlap on its sealing surfaces. If the backpressure required to overcome the valves is less than that likely to be seen in a UBA with a wet canister and pads, then a replacement should be investigated.

5. Adequate diver thermal protection is paramount for long duration UBAs. The production model of the PDTPS should be tested as a complete package with the MK 16. Knowledge of the suit's performance will provide guidance to the fleet for operational dive planning.

6. For a working diver a freshly charged oxygen bottle lasts approximately the same time as the carbon dioxide canister. If one dives with the same oxygen bottle used for the pre-dive set up and calibration of the sensors then the canister performance may exceed the oxygen duration.

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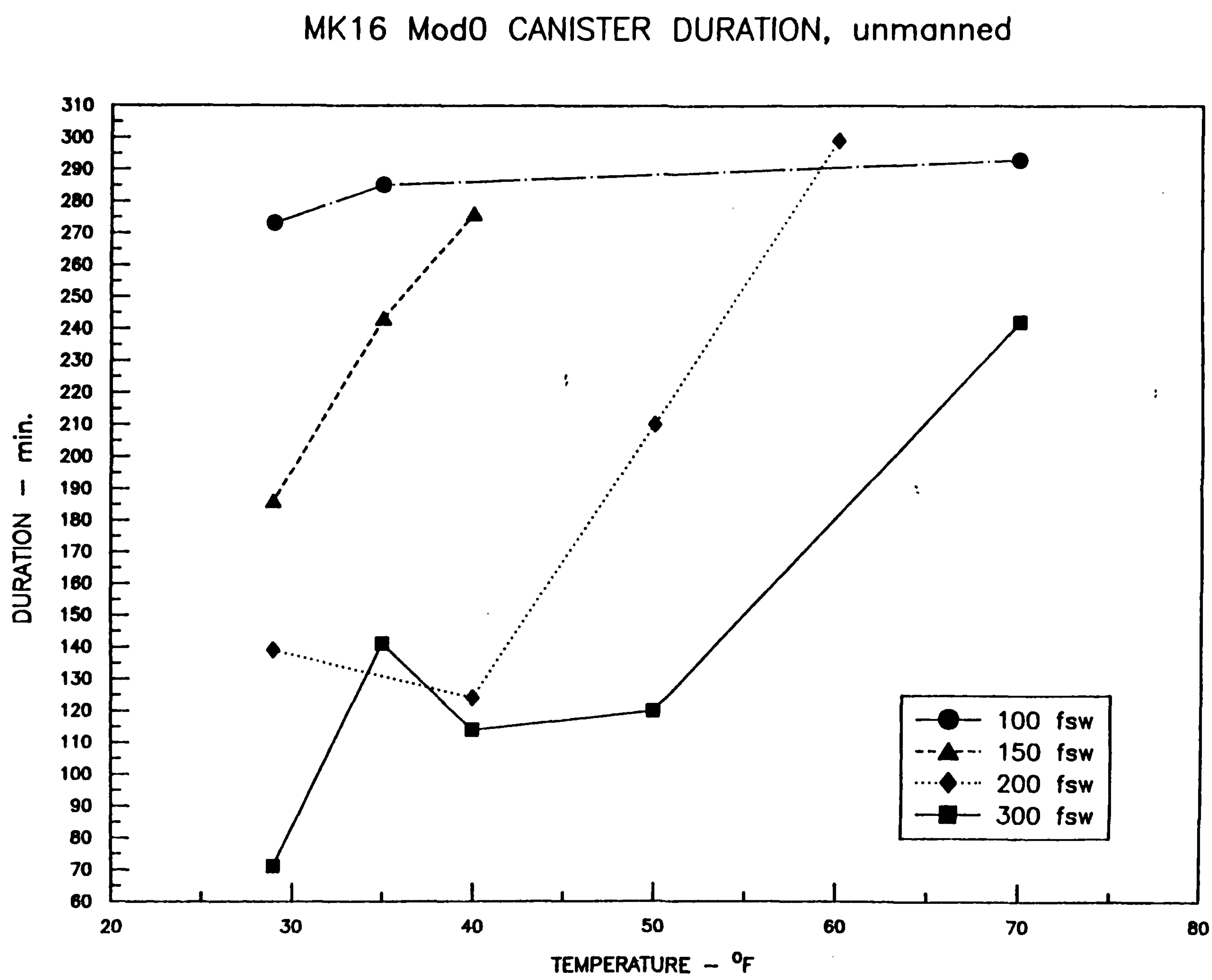
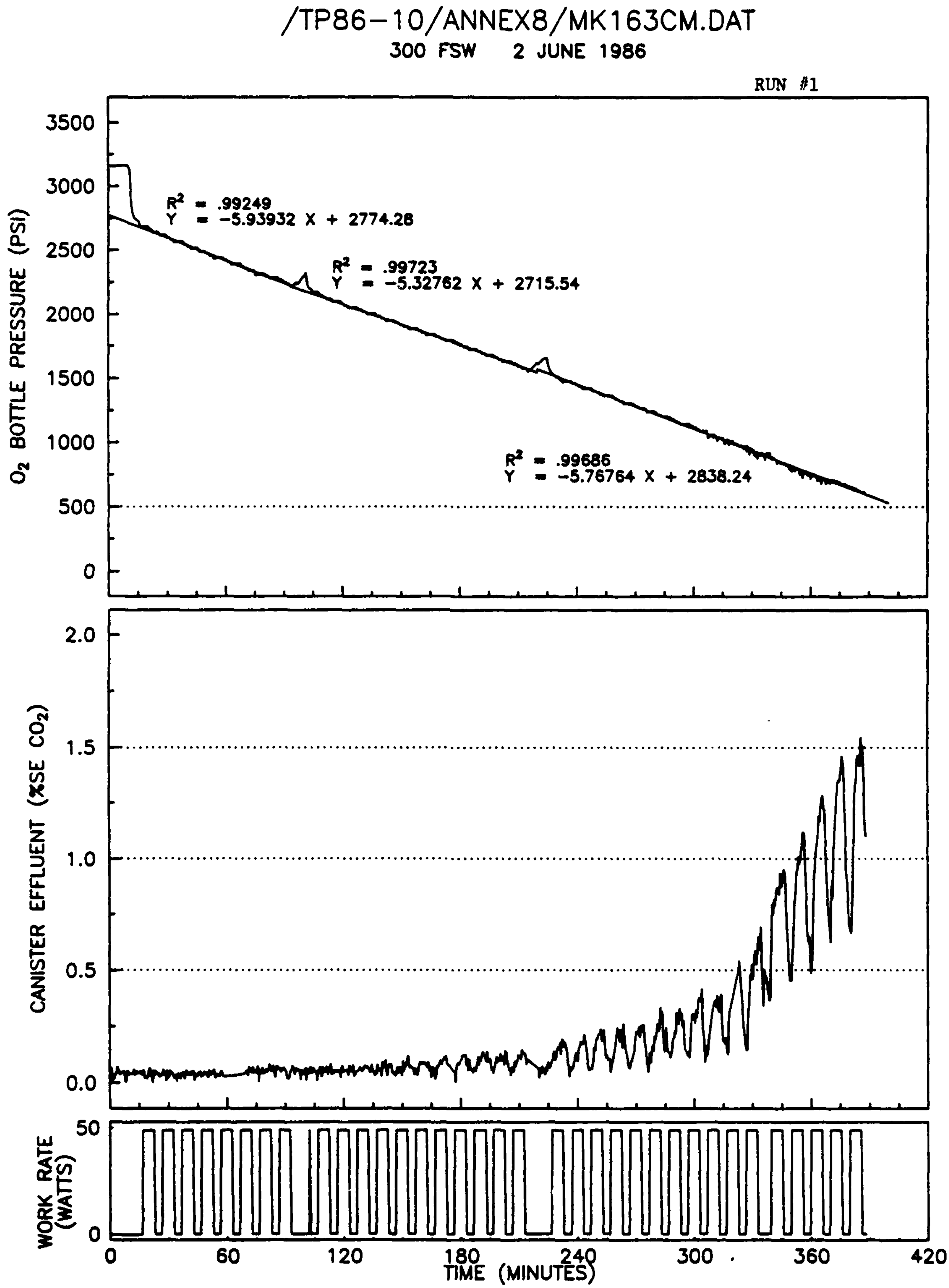

MK16 Mod0 CANISTER DURATION, unmanned
DURATION – min.
TEMPERATURE – °F
310
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
20
30
40
50
60
70
80
100 fsw
150 fsw
200 fsw
300 fsw

Figure 1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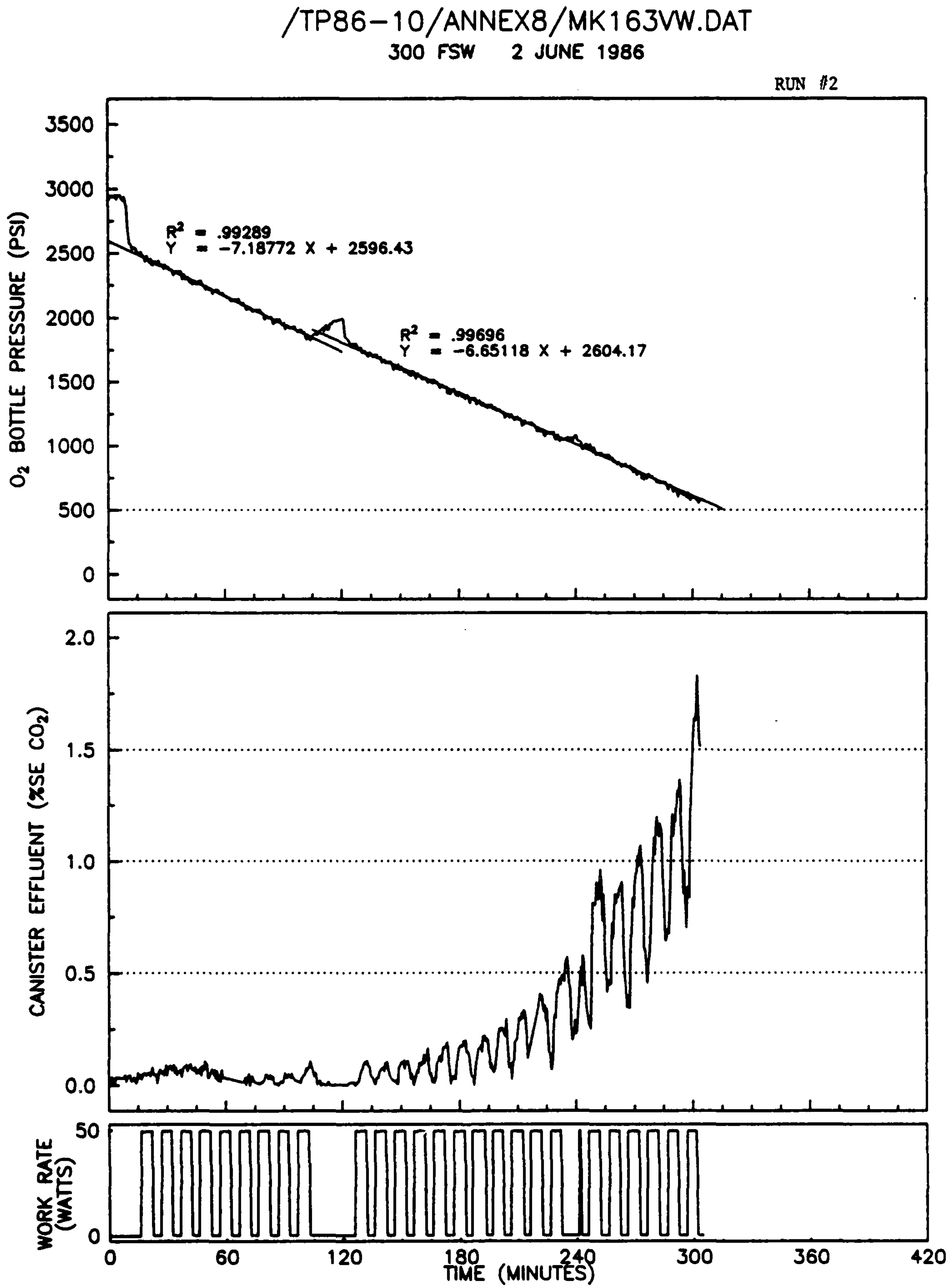
300 FSW 2 JUNE 1986
RUN #1
O2 BOTTLE PRESSURE (PSI)
R² = .99249
Y = -5.93932 X + 2774.28
R² = .99723
Y = -5.32762 X + 2715.54
R² = .99686
Y = -5.76764 X + 2838.24
CANISTER EFFLUENT (%SE CO2)
WORK RATE (WATTS)
TIME (MINUTES)
0
60
120
180
240
300
360
420

Figure 2



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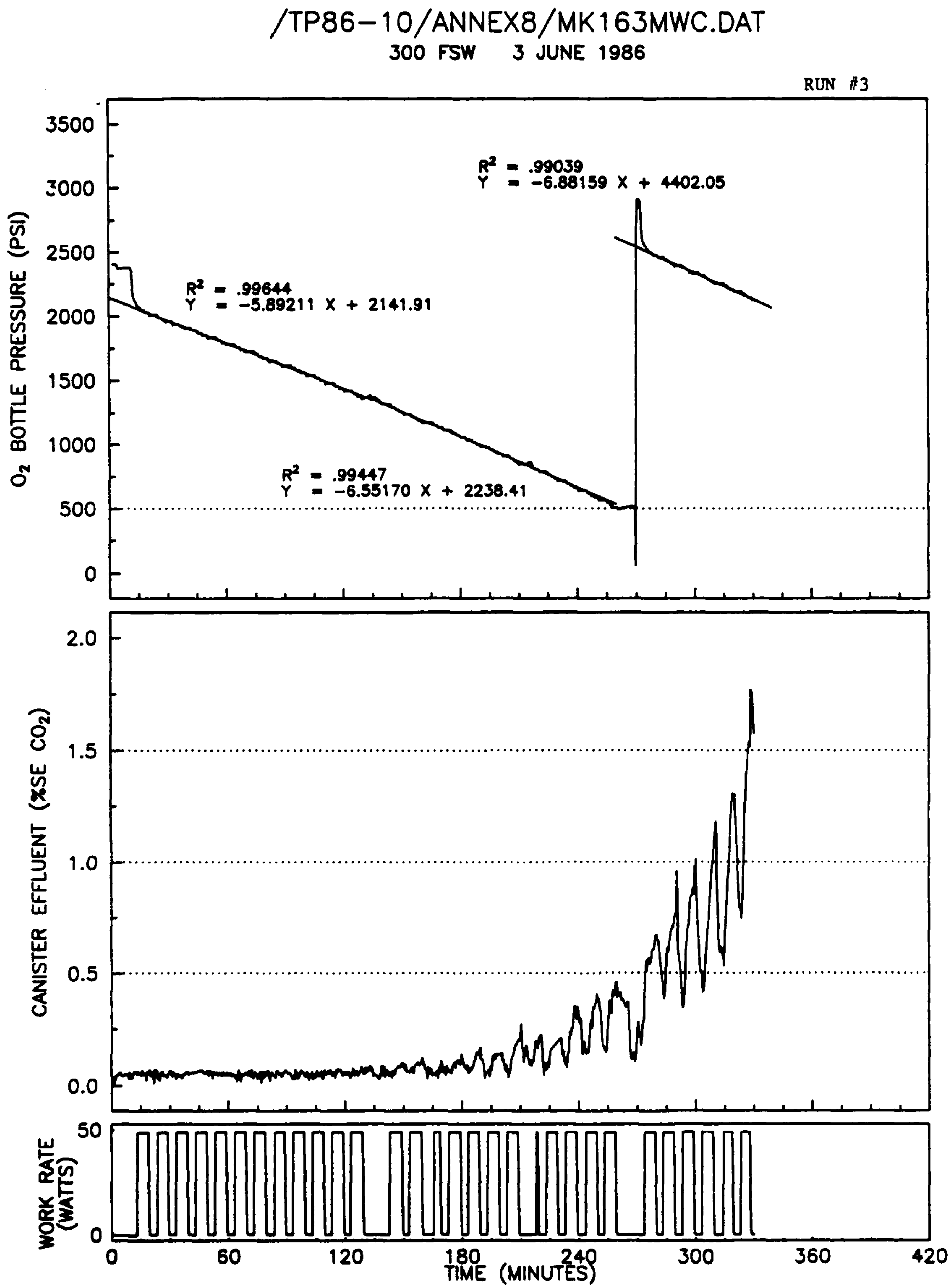
300 FSW 2 JUNE 1986
RUN #2
R^2 = .99289
Y = -7.18772 X + 2596.43
R^2 = .99696
Y = -6.65118 X + 2604.17
O_2 BOTTLE PRESSURE (PSI)
3500
3000
2500
2000
1500
1000
500
0
CANISTER EFFLUENT (%SE CO_2)
2.0
1.5
1.0
0.5
0.0
WORK RATE (WATTS)
50
0
0
60
120
180
240
300
360
420
TIME (MINUTES)

Figure 3



/TP86-10/ANNEX8/MK163MWC.DAT
300 FSW 3 JUNE 1986
RUN #3
R^2 = .99039
Y = -6.88159 X + 4402.05
R^2 = .99644
Y = -5.89211 X + 2141.91
R^2 = .99447
Y = -6.55170 X + 2238.41
O_2 BOTTLE PRESSURE (PSI)
3500
3000
2500
2000
1500
1000
500
0
CANISTER EFFLUENT (%SE CO_2)
2.0
1.5
1.0
0.5
0.0
WORK RATE (WATTS)
50
0
0
60
120
180
240
300
360
420
TIME (MINUTES)

Figure 4

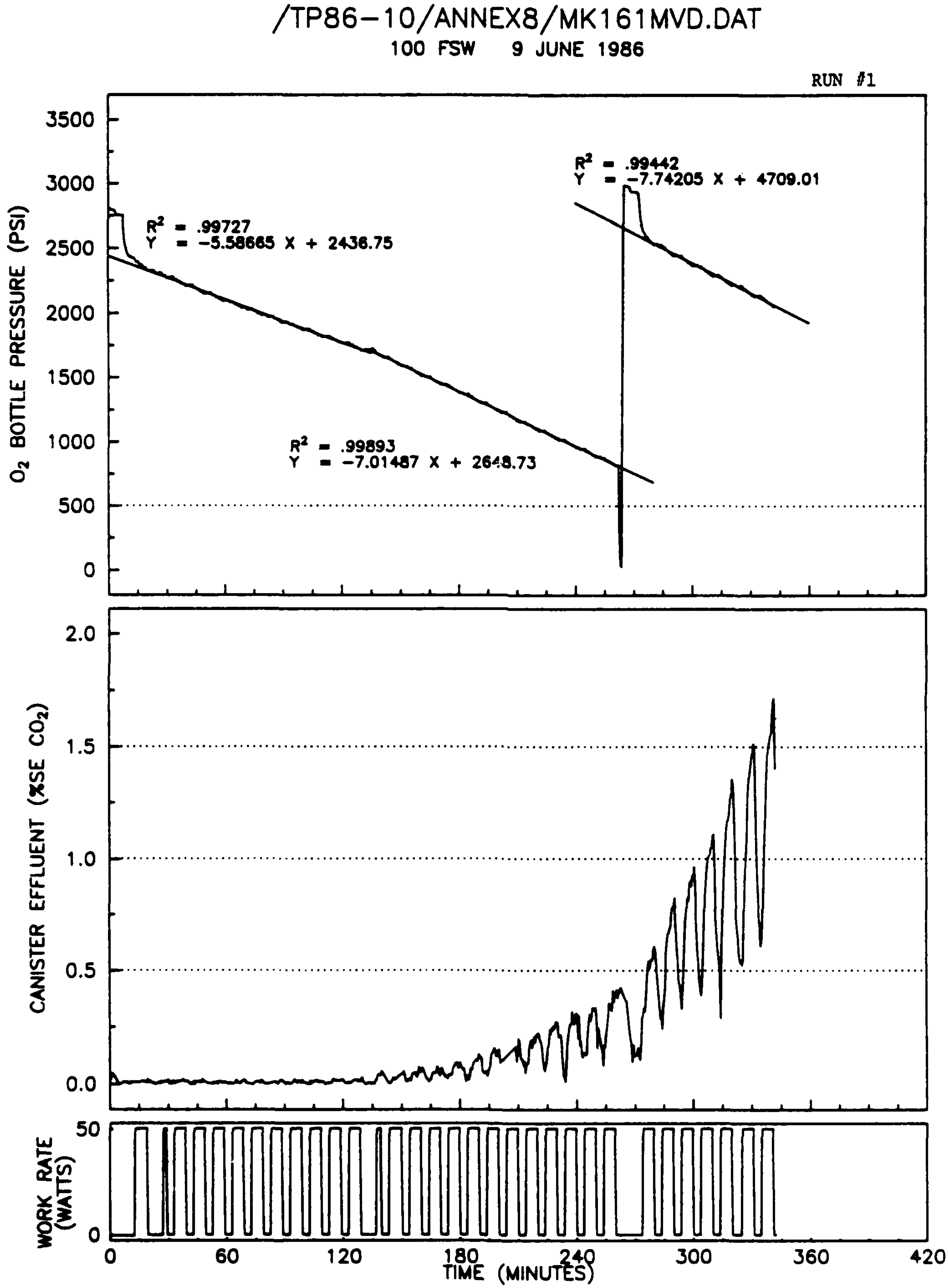
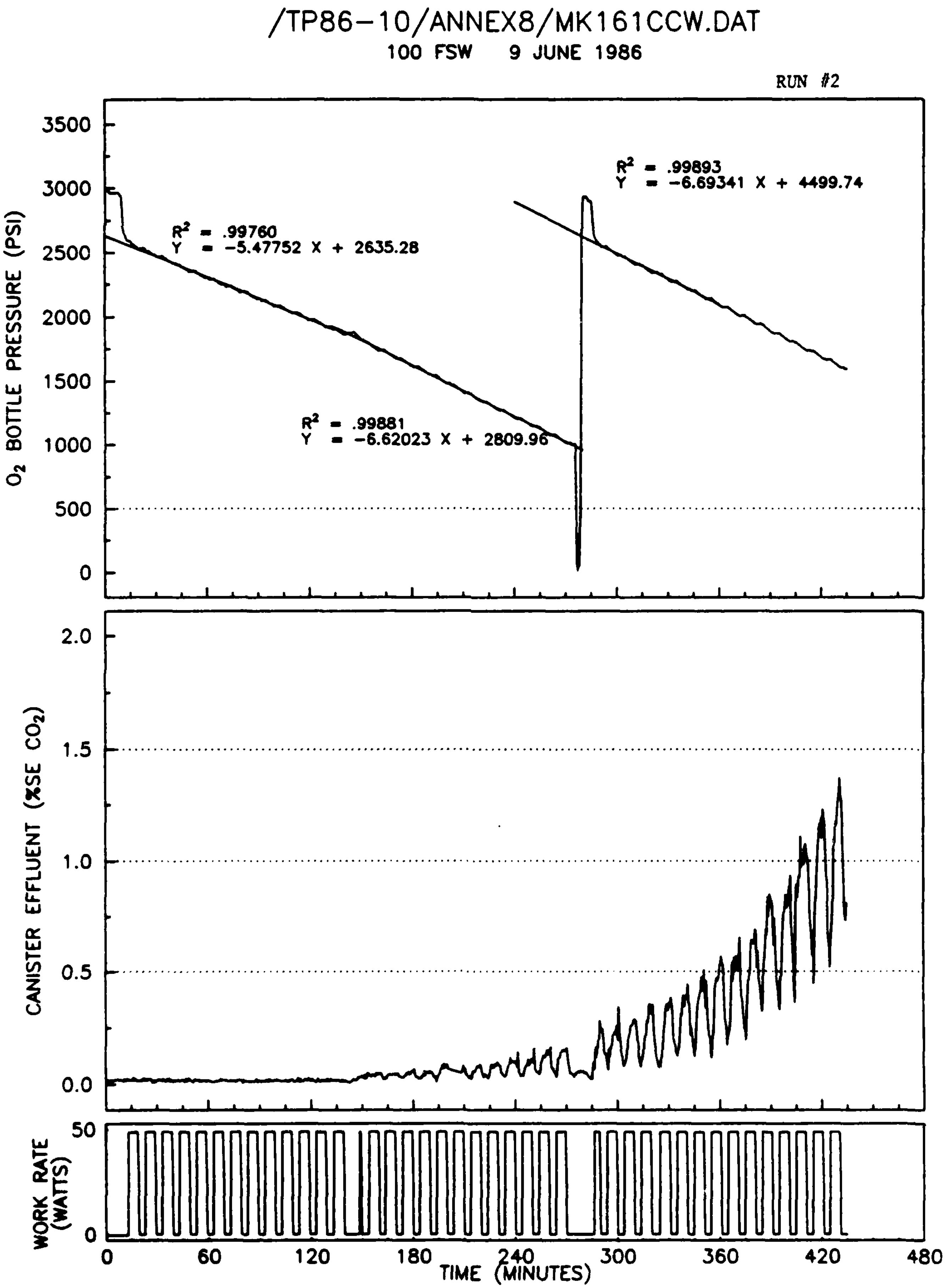

/TP86-10/ANNEX8/MK161MVD.DAT
100 FSW 9 JUNE 1986
RUN #1
R^2 = .99727
Y = -5.58665 X + 2436.75
R^2 = .99442
Y = -7.74205 X + 4709.01
R^2 = .99893
Y = -7.01487 X + 2648.73
O_2 BOTTLE PRESSURE (PSI)
3500
3000
2500
2000
1500
1000
500
0
CANISTER EFFLUENT (%SE CO_2)
2.0
1.5
1.0
0.5
0.0
WORK RATE (WATTS)
50
0
0
60
120
180
240
300
360
420
TIME (MINUTES)

Figure 5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100 FSW 9 JUNE 1986
RUN #2
R^2 = .99893
Y = -6.69341 X + 4499.74
R^2 = .99760
Y = -5.47752 X + 2635.28
R^2 = .99881
Y = -6.62023 X + 2809.96
O_2 BOTTLE PRESSURE (PSI)
CANISTER EFFLUENT (%SE CO_2)
WORK RATE (WATTS)
TIME (MINUTES)

Figure 6

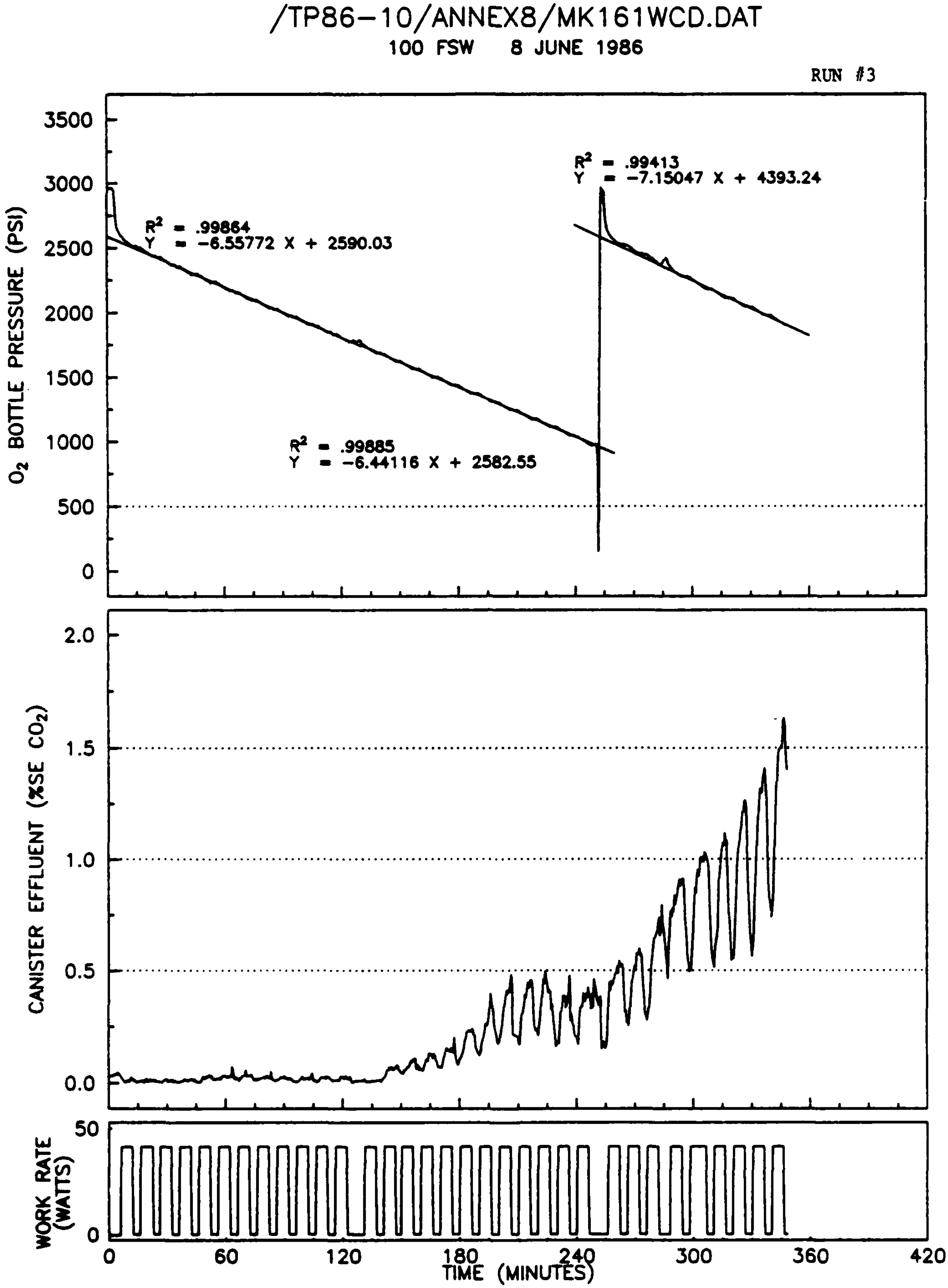

/TP86-10/ANNEX8/MK161WCD.DAT
100 FSW 8 JUNE 1986
RUN #3
O2 BOTTLE PRESSURE (PSI)
3500
3000
2500
2000
1500
1000
500
0
R2 = .99864
Y = -6.55772 X + 2590.03
R2 = .99413
Y = -7.15047 X + 4393.24
R2 = .99885
Y = -6.44116 X + 2582.55
CANISTER EFFLUENT (%SE CO2)
2.0
1.5
1.0
0.5
0.0
WORK RATE (WATTS)
50
0
0
60
120
180
240
300
360
420
TIME (MINUTES)

Figure 7

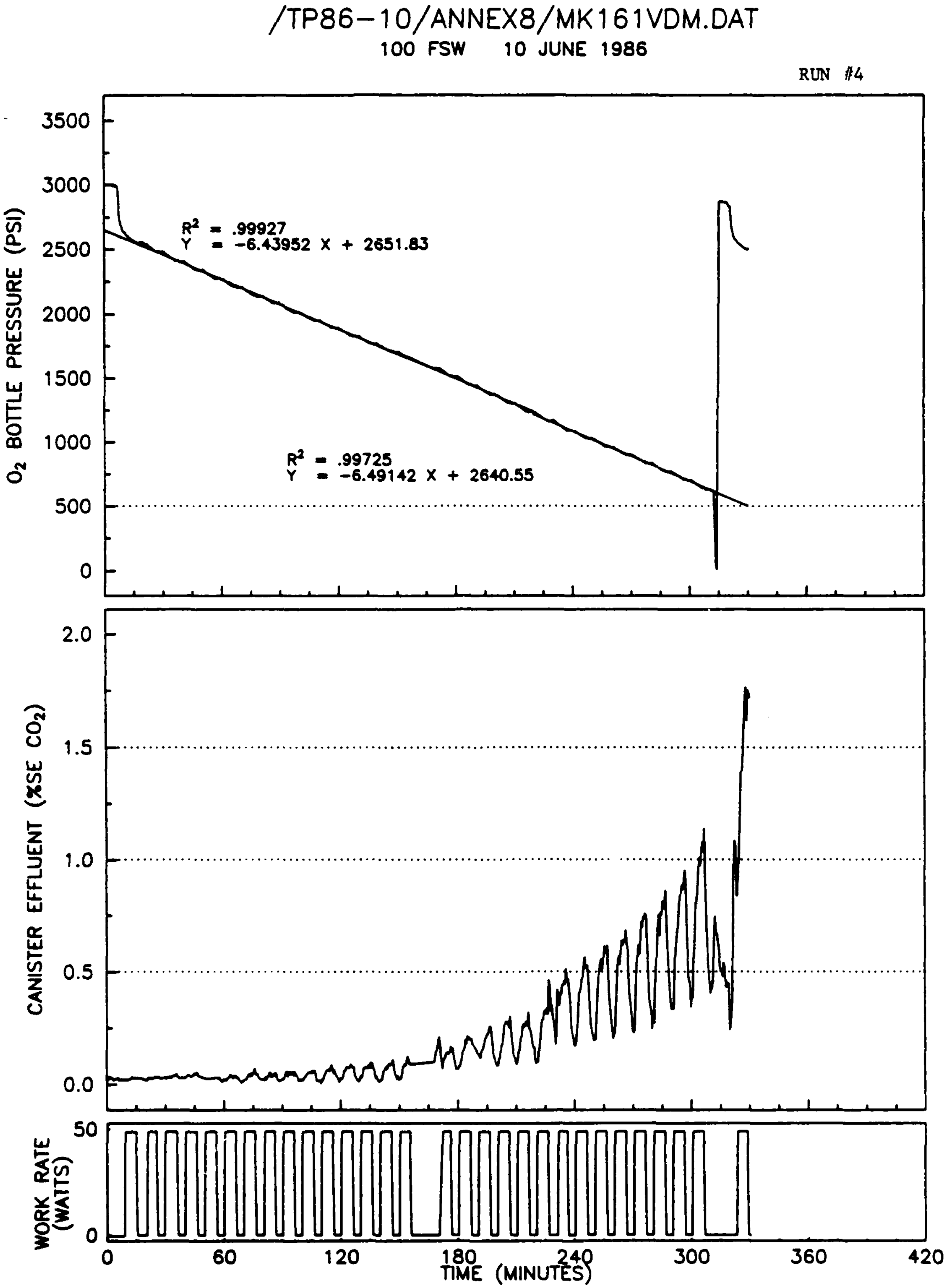
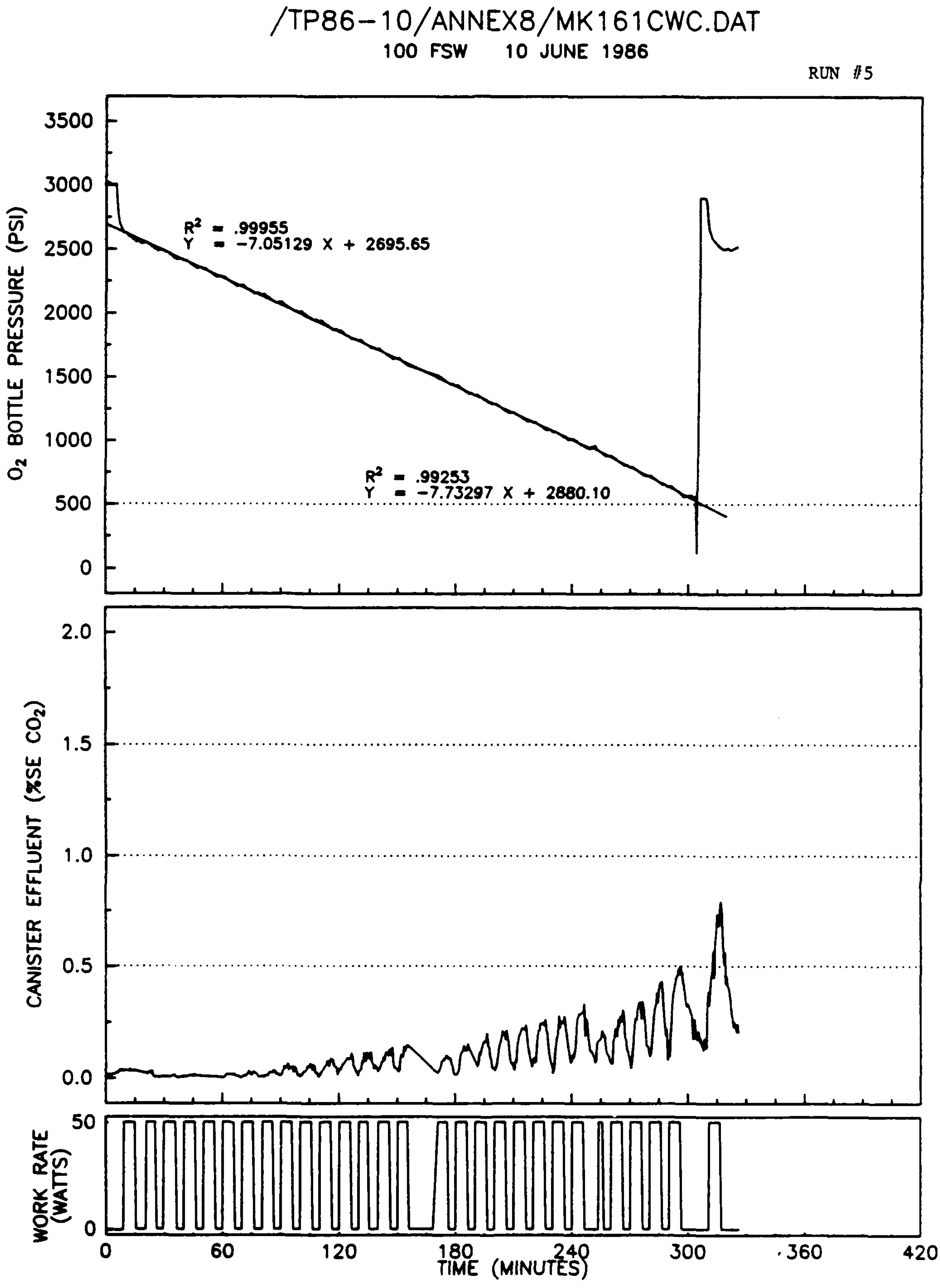

/TP86-10/ANNEX8/MK161VDM.DAT
100 FSW 10 JUNE 1986
RUN #4
O2 BOTTLE PRESSURE (PSI)
3500
3000
2500
2000
1500
1000
500
0
R2 = .99927
Y = -6.43952 X + 2651.83
R2 = .99725
Y = -6.49142 X + 2640.55
CANISTER EFFLUENT (%SE CO2)
2.0
1.5
1.0
0.5
0.0
WORK RATE (WATTS)
50
0
0
60
120
180
240
300
360
420
TIME (MINUTES)

Figure 8



/TP86-10/ANNEX8/MK161CWC.DAT
100 FSW 10 JUNE 1986
RUN #5
R^2 = .99955
Y = -7.05129 X + 2695.65
R^2 = .99253
Y = -7.73297 X + 2880.10
O_2 BOTTLE PRESSURE (PSI)
3500
3000
2500
2000
1500
1000
500
0
CANISTER EFFLUENT (%SE CO_2)
2.0
1.5
1.0
0.5
0.0
WORK RATE (WATTS)
50
0
0
60
120
180
240
300
360
420
TIME (MINUTES)

Figure 9

END

2-87

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